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U. S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Weather Service

SNOW SQUALLS IN THE LEE OF LAKE ERIE AND LAKE ONTARIO

A Review of the Literature

Jerry D. Hill

Eastern Region
Garden City, N.Y.

A[...]st 1971

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(Continued On Inside Rear Cover)

UNITED STATES DEPARTMENT OF COMMERCE
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
NATIONAL WEATHER SERVICE EASTERN REGION
Garden City, New York

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SNOW SQUALLS IN THE LEE OF LAKE ERIE AND LAKE ONTARIO

A Review of the Literature

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SCIENTIFIC SERVICES DIVISION
Eastern Region Headquarters
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ABSTRACT

A survey of the literature concerning snow squalls in the lee of Lake Erie and Lake Ontario is presented. Sections in this survey furnish information on the general snow distribution, causitive mechanisms, a numerical prediction model and modification potential of the squalls. A bibliography is also included.

SNOW SQUALLS IN THE LEE OF LAKE ERIE AND LAKE ONTARIO

I. SNOW DISTRIBUTION AND IMPACT

The mean snowfall distribution over the states bordering Lakes Erie and Ontario (see Figure 1) dramatically indicates the effect of the lakes and higher elevations on the distribution of snow in the prevailing westerly winter circulation. This distribution reflects the sum total of the environmental processes affecting the region. Generally all are related to the passage of mid-latitude cyclones across the area during the winter. Warm front activity and cold frontal passages are associated with the cyclones themselves while post cold front lake squalls add additional snow amounts long after the cyclones have left the area. Orographic effects operate to modify both the cyclones and lake squalls. These effects add an extra increment of snowfall and extend the snow season at higher elevations.

Comparison of annual snowfall and topographic maps (Figure 2) show snow belt areas consistently on the lee side of the lakes and the windward side of higher terrain. The average annual snow distribution shows up to twice as much accumulation on the lake side of the higher terrain as there is on the eastern slopes where there is no lake effect. It is generally accepted (15) that orographic effects add 5 to 8 inches of mean annual snowfall per 100 foot increase in elevation. Therefore any additional excess is likely due to the presence of the lakes.

Off the southern and eastern shores of Lake Ontario, the area of New York from Rochester to Watertown and eastward across the Adirondacks receives more snow than any place east of the Rocky Mountains (Figure 1). Parts of the area receive an average in excess of 150 inches of snow per year with minimum amounts of 70 to 100 inches along the lake shore. As an example of how both the lake and higher terrain operate together to enhance snowfall: Oswego on the eastern end of the lake receives about 90 inches per year while Bennett's Bridge at an elevation of 660 feet and 15 miles east of the shore receives 190 inches per year. Further east, Boonville, with an elevation of 1500 feet and 50 miles from the shore, receives an average of 209 inches per year.

The Lake Erie snowbelt begins just south of Buffalo and extends southwestward across the northwestern corner of Pennsylvania and into the northeastern corner of Ohio. Amounts in this area are slightly less than the Lake Ontario maximums with mean snowfall reaching about 160 inches in extreme southwestern New York, where elevations rise to about 1500 feet above the level of Lake Erie.

It is primarily the post-cold-front snow squalls that are discussed in the remainder of this paper for they can contribute extended periods of extremely inclement weather long after post frontal clearing would have occurred in another section of the U.S. When the squalls are well-developed, there may be less than 12 hours between the last squall and snow arriving ahead of another approaching weather system.

The outstanding characteristic of these lake-effect storms is their narrow banded structure causing localized snow squalls over and to the lee of the lakes. The bands may persist for several days in the very cold post frontal flow while changing their shape and orientation in response to shifts in the winds aloft. In a study (8) of snow squalls over Lake Erie during November, December, and January of three winters, there were 64 days noted with lake effect snows out of 309 total days.

These storms exert powerful economic pressure on western New York especially that due to traffic delays and massive snow removal tasks. Additional building costs are incurred for construction in the snow belt areas to make buildings strong enough to withstand possible structural failure due to snow loading.

There are a few positive benefits to the lake influence on the weather. In the fruit belts near the south shores of the lakes, the spring warm-up is 2 to 3 weeks behind the inland areas because of the effect of the cold water. In this area the trees bloom so late there is little danger from frost. The frequent abundant snowfalls provide favorable conditions for ski enthusiasts and a number of well known ski resorts are located within the snowbelts. While the deep snowcover represents a considerable water resource, there remains an ever present winter season danger of flooding during occasional thaws.

II. GENERAL OBSERVATIONS

During short periods of up to three days when all precipitation is caused by snow squalls, heaviest snow accumulations sometimes occur very near the lake shore. This snow falls from convective type clouds which form in cold unstable air that is heated by passage across warmer lake water. It is generally agreed that the large scale synoptic effects conducive to developing squalls are:

1. A strong flow of cold arctic air across the lakes after a low pressure center has moved into eastern Canada.

2. A southwestward extension of the parent Low in the form of a trough over the Great Lakes.

3. A trough aloft over the eastern U.S. and Canada which frequently stagnates or broadens to the west.

Typical surface and upper air features associated with heavy squalls are shown in Figure 5.

The snow squalls have a characteristic banded structure in the form of narrow elongated areas oriented either parallel to the general wind direction or to a shoreline. Overlake storms usually form far away from the shoreline when winds aloft are approximately along the major axis of the lake. These storms usually appear as a single narrow band and stream inland with the prevailing wind. The band is usually 2 to 20 miles wide and 50 to 100 miles long.

The second type of storm is the shoreline type which generally forms with a more northwesterly flow and thus shorter overwater trajectory. Precipitation with the shoreline storm generally begins along the downwind shore and may stream inland as several short lines 1 to 5 miles wide and 25 to 50 miles long. A single overlake band may change to a shoreline band in response to changes in the winds aloft.

Tops of the snow squalls seldom reach 10 thousand feet but are characterized by extreme instability. This is indicated by the high rates of snowfall, thunder, and lightning which accompany the more severe storms. Some recently summarized characteristics of lake effect snow bands are shown in Table 1 (Page 18).

Many cases of extreme snow occurrences associated with the snow squalls have been documented. During a storm of December 6-11, 1958, Oswego, New York received a total of 70 inches of snow while Bennetts Bridge and Boonville, further away from Lake Ontario but at higher elevations, received 41 and 31 inches respectively. The local extent of this storm is indicated by the fact that snowfall greater than 24 inches was restricted to an area 25 miles wide. At the height of the development of this band it deposited 45 to 50 inches of snow in a 17-hour period (10).

Oswego was hit even harder during the period January 27-31, 1966 when a pair of cyclones moving along the east coast combined with the lake effect to produce 101 inches of snow in a 5 day period (17). The first phase of this storm consisted of a Low moving up the east coast to Newfoundland. No cyclonic precipitation reached as far west as Oswego but arctic air moving in behind the Low developed a single narrow band of snow by the evening of the 27th. Winds were west-southwest in gusts to 40 MPH and by noon of the 28th a total of 20 inches of new snow was on the ground. The band then oscillated north and south of the city while winds diminished to nearly calm on the 29th. The snow was light and fluffy with a water equivalent of 29:1. The third phase occurred on the 30th when another Low moved up the east coast to Labrador. This time cyclonic precipitation reached Oswego and deposited 12 inches of snow. A change to lake effect snow was identified by a change in the snow crystal structure on the night of the 30th. During the remainder of the night and all day on the 31st winds gusted to 87 MPH while an additional 58 inches of snow was recorded. On February 1st when the snow had ended, water equivalent was measured as 2.6:1 in the sides of drifts facing the wind. This represents vast amounts of snow packed into the drifts by the wind.

Water content of the lake effect storms is quite variable and generally ranges from 6:1 up to about 50:1. The average is about 18:1. In January, 1940, Watertown, New York had a total snowfall of 79 inches and a total liquid precipitation equivalent of 2.84 inches or an average ratio of 27:1 for the month (13).

Although not regularly associated with such extremes as Lake Ontario, Lake Erie is still responsible for significant accumulations on its lee shore. A storm on October 18-19, 1930 occurred when the lake water was still comparatively warm at 59°F. Westerly winds deposited 48 inches of snow 15 miles south of Buffalo. Only six inches fell in South Buffalo! Another early storm, on October 24, 1937, occurred with a west-northwest wind. A maximum .7 inch water equivalent fell just south of Buffalo and a secondary maximum occurred in Northeastern Ohio near Jefferson (14). These examples are indicative of the tendency for shoreline bands to develop over the south shore with northwest winds while a westerly wind produces a single narrow band at the eastern end of the lake.

It is interesting to compare the distribution of snow near each of the lakes after snow squalls have affected both simultaneously. Figure 3 demonstrates that the largest accumulation occurred near the Lake Erie shore while near eastern Lake Ontario the center of heaviest fall was somewhat inland. The reasons for this are apparent from Figure 2 which shows the 1000 foot elevation contour quite close to the Lake Erie shore from Erie, Pennsylvania to Dunkirk, New York. This provides a very steep prominence in the path of the onshore wind while the terrain near Lake Ontario slopes much more gradually although ultimately to a higher elevation. Thus the snowsqualls are subjected to a sudden lifting near Lake Erie and an immediate enhancement of the precipitation process while those moving into the area near Lake Ontario receive a more prolonged lift whose maximum effect occurs some distance downwind.

III. MECHANISMS

Brooks (1) was apparently the first to study snowfall distribution near the Great Lakes when he reviewed data for the period 1895-1910. The observing and reporting network at that time was not sufficiently dense to reveal many of the variations we are now able to perceive. For instance Brooks indicated only a maximum of 70 inches per year near eastern Lake Erie and none of the orographic effects near there. He did however reveal larger amounts near eastern Lake Ontario and into the higher elevations of the Adirondacks with average snowfall of 200 inches a year at Oswego and an absolute maximum of 300 inches in one year at Adams which is between Oswego and Watertown.

Regular observing methods in 1915 were not sufficient to reveal the existence of narrow snow squall bands and Brooks could only speculate on the reason for the enhanced accumulation near Lake Ontario. He postulated that moist cyclones in winter cause increased precipitation when blowing from a comparatively warm water surface over cold land and this effect was increased by local topography. Some of the late winter increase was believed due to ice floes collecting on the leeward side of the lakes and presenting a surface from which the wind could blow loose snow onto the land.

As observing networks and communications were improved, much additional knowledge was learned about the behavior of the lake storms and several of the contributions to their development. The effect of friction was better understood leading to an explanation as to how the wind speed increases over the smooth lake surface, then becomes retarded by the roughness of the lee shore. The resulting speed convergence produced over the lee side of the lake yields forced ascent.

The thermal influence of the lake was found to operate in several ways. The heating of the cold air over the warm water caused the air to rise and lift the height of the inversion at the top of the arctic air thus giving a greater depth for convection. Remick (13) investigated this effect by comparing radiosonde observations for the same air mass as it moved from Joliet, Illinois, to Buffalo, New York and found the inversion height raised from .8 km. to 2 or 3 km. by its flow across the lake. Large temperature differences between the lake and the air were found to produce steeper lapse rates allowing more moisture to be evaporated into the air and saturation more easily achieved.

A typical lake effect snow is illustrated in Figure 4. On the downwind shore are symbolized the different types of snow which can be identified as characteristic of the lake squalls. The physics of the process which produces the different types at unique distances inland is described in (2).

General observations of conditions favorable to lake snows were summarized by Wiggin (18):

1. The existence of a strong flow of cold air across the lakes with a lee shore lapse rate that is adiabatic or greater to over 5000 feet.

2. Cyclonic curvature of the flow pattern. Anti-cyclonic curvature may produce numerous flurries but little accumulation.

3. A temperature difference of at least 10° C should exist between the air and water.

4. A long fetch over the water is favorable for heavy accumulation

5. Wind shear is required to produce longitudinal convective cells.

6. The band width will be about 3 times the depth of cold air. Usually 3 to 5 miles wide and 15 miles inland.

With the increased availability of weather radar to observe the behavior of the snow squalls and improved upper air sounding equipment to determine their environment, a considerable amount of research was undertaken on this phenomena during the decade of the sixties. Major participants have been Cornell Aeronautical Laboratories, The State University of New York, and Pennsylvania State University. Their recent reports have added considerably to the knowledge about lake effect storms. The ultimate goal of this research is to gain sufficient knowledge in order to devise and undertake a plan for weather modifiction.

Numerous storms were investigated and asessed by their common factors in spite of the great variety and intensities of the resulting snow pattern. A typical storm examined was one in which there was southeastward penetration of cold air across the Great Lakes and the development of a broad trough from the parent Low into the lakes region (8). It revealed several interesting microscale details.

A microscale pressure analysis showed a weak trough in the lee of each of the lakes. The trajectory of the air reaching western New York came from south of Lake Superior, through Illinois, Indiana, Ohio, and western New York. Air over Lake Superior moved southeastward over Lake Huron and was recurved eastward over the Ontario Peninsula. The low level wind field revealed a confluence line over Lake Erie between two persistent wind regimes having a 20 to 60 degree difference in direction. Flow to the south of the confluence line was southwest to south-southwest for 50 to 100 miles south and east of the lake shore with a strong cross-isobar component of 60 to 90 degrees. Flow to the north of the confluence line was west to west-northwest for about 25 miles north of the lake shore.

A study has been made (11) of a similar confluence band that occurred over Lake Ontario during a storm on February 3-4, 1965. A snow band developed over the lake in a cold post-frontal flow and extended downwind to the eastern shore. A persistent convergence zone was determined through analysis to exist under the northern edge of the snow band and was sharp enough to be apparent from synoptic wind direction observations. The band oriented itself parallel to the winds aloft above the gradient level and rotated in response to changes in the winds aloft. As the band moved, surface wind shifts of 25 to 90 degrees were observed over a narrow distance under the northern edge of the band. Most of the snow was observed along and south of the wind shift line with an accumulation at one point of 9 inches in 4 hours. The band paralleled the pressure field but the gradient was consistently stronger south of the band than north of it. Isallobaric analysis consistently showed maximum falls leading the band as it oscillated north and south during the two days.

The most intense single band storms over the lakes appear to have many similarities in wind structure and distribution. The surface convergence line appears to be a definite feature of the snowbands and not just a local wind anomaly associated with individual convective cells. A comprehensive 3-dimensional study of a typical line (9) reveals low level inflow from the surface to 1.5 km. with the strongest inflow on the south side. Outflow exists from 1.5 km. up to the cloud top. The strongest lateral inflow and outflow are on the south side of the band consistent with qualititive features determined from radar, showing a sharp northern edge and diffuse southern edge. This diffuse southern edge may be the result of advection of snow crystals out of the main cells in the high level outflow.

The convergence line persists as long as banded precipitation exists and becomes established as soon as a new band of precipitation is observed on radar. The line may disappear with the last cells of a dying band and suddenly reappear elsewhere with a new band of developing cells. The individual cell echoes appear to move with the speed of the mean winds in the cloud layer. If the winds change gradually and by less than 30 degrees, the cells move at a slight angle with the wind and the band changes orientation until it again parallels the winds aloft. A substantial wind shift aloft causes a change in direction of cell movement and resultant rapid migration of the line, in which case it usually moves to a lee shore and becomes a shoreline band or completely disorganized.

movement and resultant rapid migration of the line, in which case it usually moves to a lee shore and becomes a shoreline band or completely disorganized.

An investigation was made to determine the addition of heat to air during flow over Lake Erie (8). Maximum heating occurred at the low levels and the largest value of 3° C occurred as the coldest air moved over the lake. The top of the heated layer gradually increased from 1400 to 2300 m. The maximum heating rate was observed to be .37 cal. cm.$^{-2}$ min.$^{-1}$ and this compares to a maximum upward heat flux of .5 cal. cm.$^{-2}$ min.$^{-1}$ observed over dry land on a sunny day. The total heating for a 125 mile fetch over the lake ranges from 42 to 89 cal. cm.$^{-2}$ representing an extremely rapid modification of the air mass.

Recent studies allow a few conclusions to be drawn which widen the scope of previous knowledge of the lake effect. The existence of marked low level confluence bands was not previously suspected to make such a large contribution. The mobility in orientation and position of bands over the lake appear to rule out sea breeze, frictional convergence, or orographic effects as primary mechanisms controlling the shape, location, and movement of the storms. However, any or all of these effects may intensify a storm, once formed, by the heating of the air from below. Finally, heavy snowfall rates appear possible because of concentration of moisture into narrow convergence zones.

IV. A NUMERICAL MODEL

At Pennsylvania State University, Lavoie developed a numerical model (2) of the Lake Erie circulation during periods of intense snow squall activity. The model was made as consistent as possible with the existing hypotheses on mechanisms but it became clear that a compromise had to be made between broad applicability of the results and the fact that computer limitations preclude resolving the distribution of the dependent variables in three dimensions.

In the model, the atmosphere consists of three layers which can be defined by distinctive lapse rates of potential temperature. The calculation of time dependent quantities is restricted to a dry homogeneous middle layer bounded by a material upper surface such as an inversion whose height may vary as the result of mean divergence within the middle layer. It is bounded on the bottom by a layer in contact with the surface which is characterized by a superadiabatic lapse rate to represent a condition of upward heat flux. The upper limit of the lowest layer is arbitrarily set at 50 meters.

The model is applied to mesoscale phonomena whose characteristic wave length is of the order of tens of kilometers in the horizontal and less than five kilometers in the vertical. Patterns of divergence develop in the middle layer in response to horizontal accelerations which depend upon, among other things, the distribution of surface fluxes of momentum and sensible heat and upon the slope of the terrain.

The equations of motion, the first law of thermodynamics, the equation of state, and the continuity equation form the basis of the model and provide a set of four simultaneous differential equations governing the local time rate of change of the horizontal wind, potential temperature, and depth of the homogeneous middle layer. The four equations were solved by a finite difference scheme over a 40 by 50 point rectangular grid covering an area about 1200 km. by 1200 km. and centered on Lake Erie. Grid spacing is 12 km. parallel to the long lake axis and 6 km. in the cross lake direction.

At the beginning of the computation there is homogeneous distribution of the dependent variables. The lake is then uncovered while terrain relief is imposed. With specified wind direction, lake-air temperature difference, and initial inversion height, the model produced maps of vertical motion and deformation of the inversion surface. Since moisture was not included in the model, no direct comparison is possible with observations; however it can be assumed that the heaviest precipitation will come from the thickest clouds. These should be associated with the greatest depth of the mixed layer and near or slightly downwind from the maximum upward vertical motion.

Observed patterns of snowfall and of cloud distribution appeared to be very well correlated with predicted contours of the inversion surface marking the top of the mixed layer. Experiments were conducted with the model by varying the wind direction across the lake and observing the resulting vertical motion and inversion deformation fields. When the wind direction was 270 degrees, the maximum vertical motion occurred along the shore of the lake between Cleveland and Erie. The maximum lifting of the inversion also occurred along the south shore but further east between Erie and Dunkirk, New York.

A wind direction of 255 degrees produced a maximum inversion deformation further eastward than the due west wind. It occurred near Buffalo and had a larger magnitude due to its longer fetch and prolonged opportunity to be warmed by the lake. The maximum upward vertical motion also shifted eastward with one center near Buffalo and another near Erie. This agrees reasonably well with the actual case shown in Figure 3 when a wind direction of 250 degrees produced maximum amounts between Erie and Buffalo.

When the surface wind was specified to be 295 degrees, the maximum upward vertical motion and inversion deformation shifted back to the south shore. Centers of each coincided and were located near Cleveland and Erie but were not quite as strong as their westerly wind counterparts.

To assess the relative contribution of topography, heating, and friction, experiments were conducted where one or more factors was neglected under otherwise identical conditions. Under the conditions of the model and the experiment, heating provided by the lake-air temperature difference would be the single most important contributing factor to lake effect storms.

Although the location of the steady-state cloud band is indicated by the model it does not predict details such as the very narrow confluence line in the wind field associated with the intense snow bands. The addition of a moisture continuity equation to the model could give a measure of moisture flux into the cloud band and perhaps provide a basis for quantitative prediction of precipitation. Nevertheless, there is hope that the intensity of the convective motions can be uniquely related to the mesoscale features and a model similar to the one described here can be developed as a useful forecast tool.

V. MANAGEMENT POTENTIAL OF THE SNOW SQUALLS

It is only proper after considering the causes and effects of lake snow squalls to speculate on their modification potential for the benefit of the affected areas. Granted, the objectives are tenuous owing to population density and diverse commercial interests.

In lake effect storms there is an abundance of water vapor and a deficit of ice nuclei. This results in cloud hydrometeors growing very rapidly and becoming heavily rimed. The rimed crystals have greater terminal velocities and fall out nearest the shoreline whereas non-rimed crystals are advected further inland. Seeding the clouds might then alter snowfall in area or degree of impact in the following ways (9):

1. Premature nucleation of supercooled clouds to

    a. Increase deposition of snow into the lake.

    b. Extend inland areas upwind to lakeshore (when snow normally reaches the ground 5 to 10 miles inland over the hills).

2. Overnucleation of cloud system

    a. Resulting in a downwind extension of the snow area through decreased particle sizes and reduction of riming.

    b. To develop a crosswind extension of the snow band by a lateral extension of the natural nucleation zone.

3. Increase precipitation in systems giving little or no natural snowfall due to

    a. Upsetting of colloidal stability in a supercooled system by introduction of freezing agents.

    b. Addition of positive buoyancy by latent heat release.

The low temperature of most lake storm clouds is highly advantageous to seeding. In this case both overseeding with silver iodide to advect precipitation inland and seeding to promote nucleation where it is not occurring is feasible.

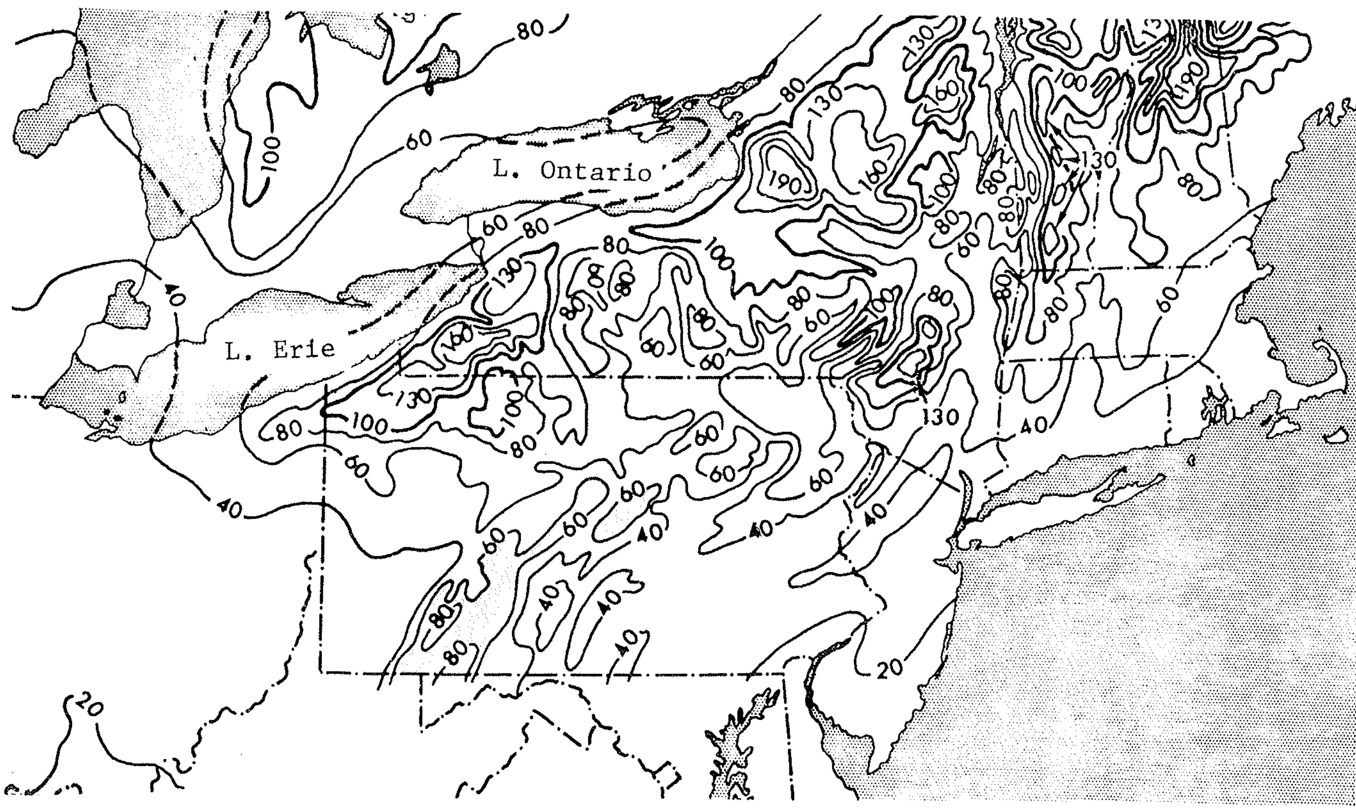


Figure 1. Mean Seasonal Snowfall. United States data is for year 1951 to 1960, Canadian data is for years 1931 to 1960. Taken from reference (10).

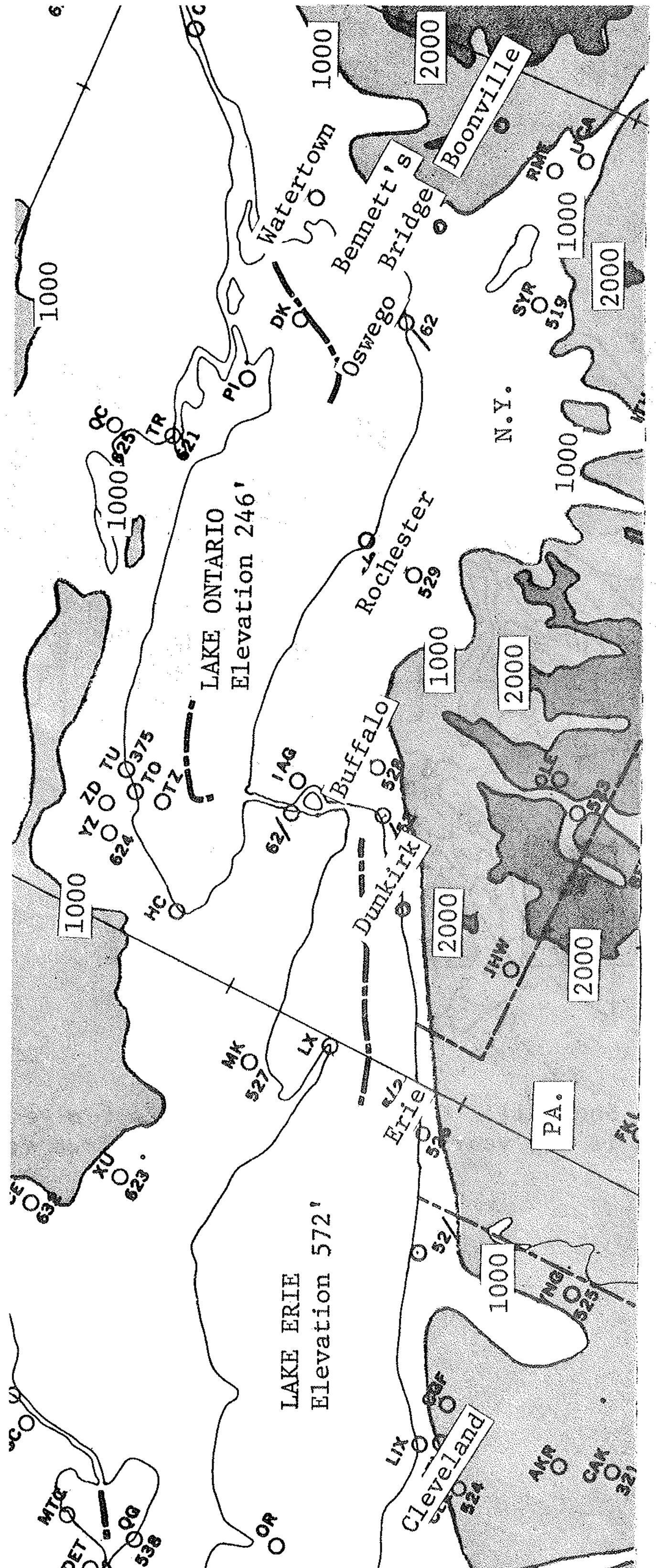


Figure 2. Smoothed Topographic Features

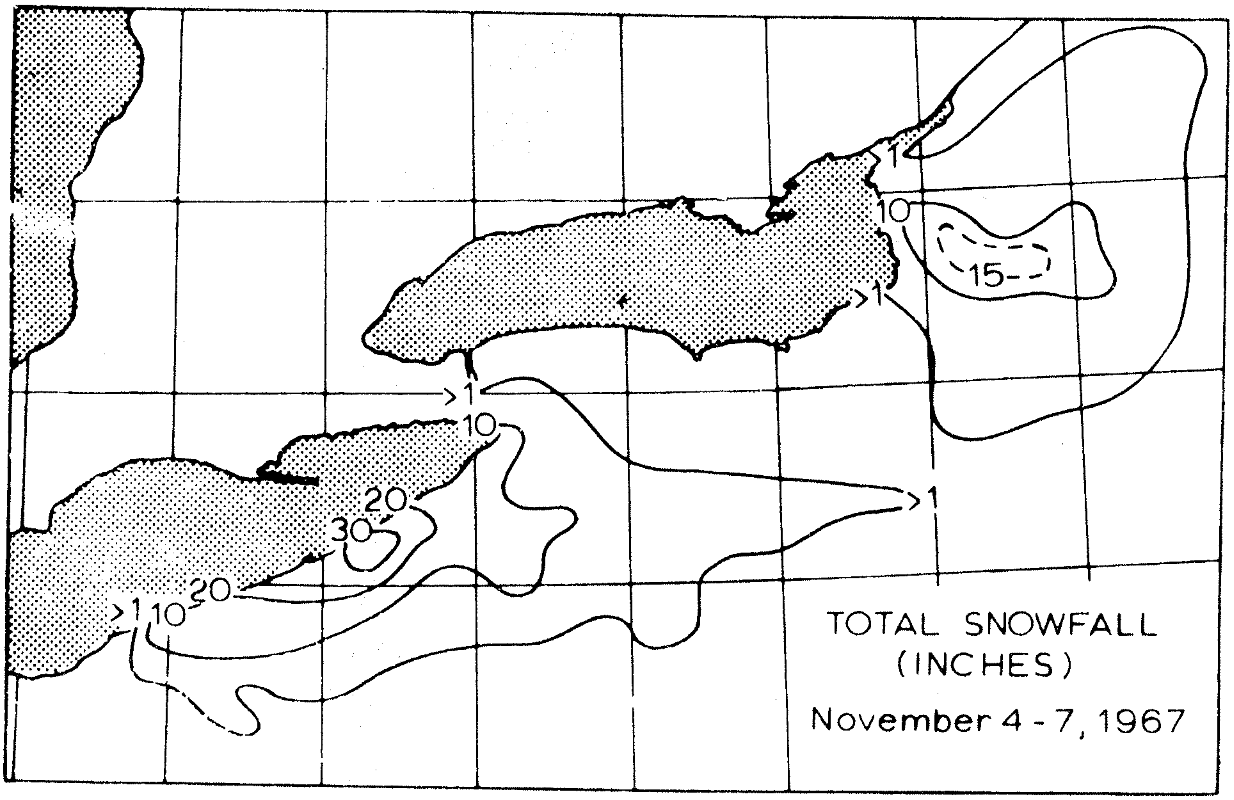


FIGURE 3. Snowfall distribution from storm, November 4-7, 1967. Taken from reference (20).

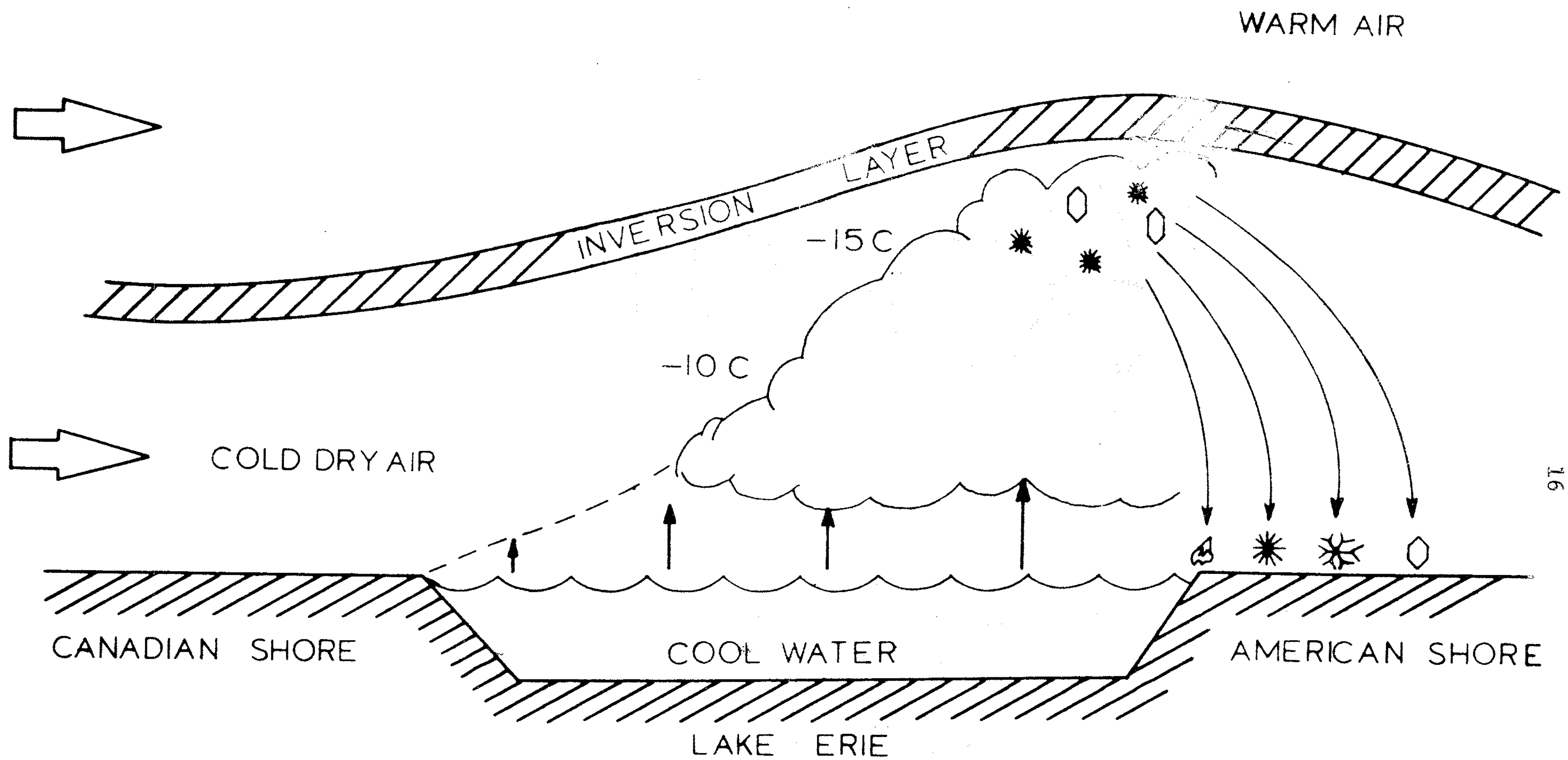
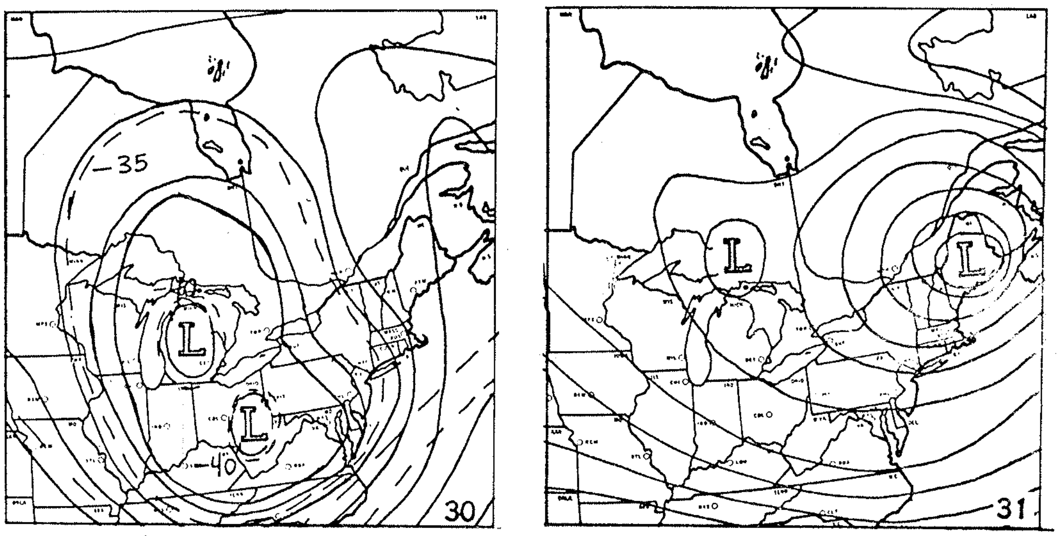
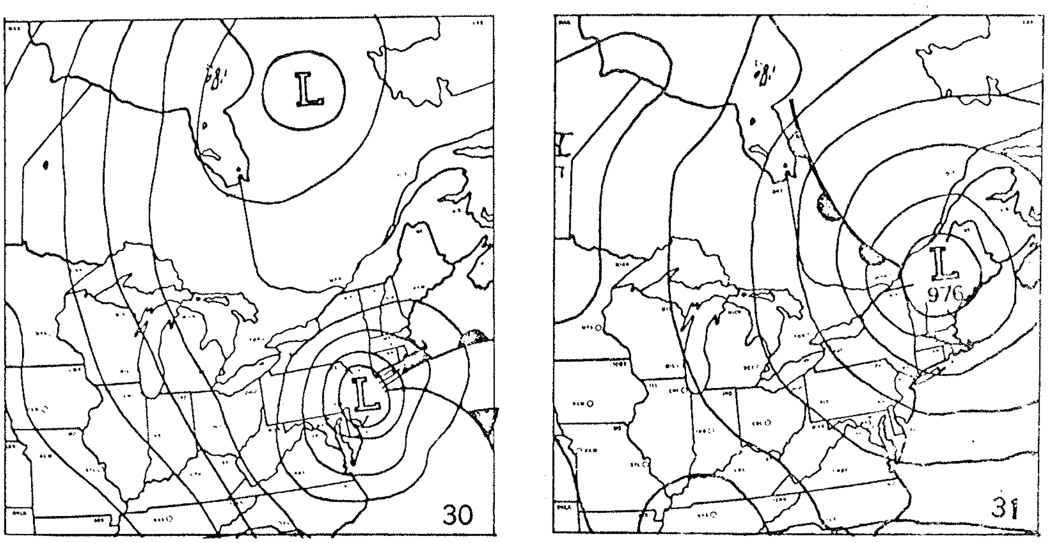


FIGURE 4. Schematic cross-section of lake effect snow. Heaviest snow crystals, rimed and graupel, fall out faster and nearest the shorelines. Lighter non-rimed dendrites and plates are carried further inland. Taken from reference (2).



Upper-air charts for 500mb surface—0700 EST, 30 and 31 January.



Surface charts—0700 EST, 30 and 31 January 1966.

Figure 5. Typical surface and upper air features associated with heavy snow squalls. Taken from reference (17).

TABLE 1

CHARACTERISTICS OF LAKE EFFECT SNOW BANDS (Taken from reference (2))

A. Mesoscale Features	A. Single Band	B. Multiple Bands
1. Precipitation	Heavy snowfall (>4 inches)	Modest snowfall (≤ 4 inches)
2. Location/Orientation	Overlake or along S shore	NW-SE bands S shore
3. Winds aloft	SW to W/15-20 m sec^{-1}	NW
4. Air temperature - Low level	-15 C to -10 C	-15 C to -5 C
5. Cells		
a. Movement	With prevailing wind	With prevailing wind
b. Echo persistence	Long (>1 hr)	Short (<1 hr)
c. Entire band "movement"	At angle to prevail wind	
6. Convergence pattern	Sharp con. line beneath storm	
7. Band dimensions (horizontal)	5-10 mi. wide; 50-100 mi. long	1-3 mi. wide; 20-50 mi. long
B. Cloud Structure		
1. Vertical extent	2 - 2.5 km	1 km
2. Bases/Tops	0.5 km / 3 km	1 km / 2 km
3. Temperature	-15 C to -30 C	-10 to -20 C
4. Horizontal dimensions	Like band dimensions	¼ to 1 mi. wide cloud streets over water fusing into continous sheet inland
C. Cloud Microphysics*		
1. Updrafts - Average	<2 m sec^{-1}	<1 m sec^{-1}
2. Liquid Water Content	0.5 - 2 g m^{-3}	0.2 - 1 g m^{-3}
3. Droplets		
a. Size (ave. radius)	5μ	
b. Concentration	300 - 500 cm^{-3}	
4. Natural ice nucleus conc.	1 - 10 Liter^{-1}	1 - 10 Liter^{-1}
5. Ice-to-water ratio (initial)	10^{-4} to 10^{-6}	
6. Ice crystal size/conc.	1 - 4 mm/ 1 - 10 Liter^{-1}	

*Tentative data obtained from sparse aircraft and ground measurements, or deducted from calculations w[illegible] appropriate

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LIST OF EASTERN REGION TECHNICAL MEMORANDA
(continued from inside front cover)

NWS ER 40 Use of Detailed Radar Intensity Data in Mesoscale Surface Analysis. Robert E. Hamilton. March 1971 (COM-71-00573)

NWS ER 41 A Relationship Between Snow Accumulation and Snow Intensity as Determined from Visibility. Stanley E. Wasserman and Daniel J. Monte. May 1971 (COM-71-00763)

NWS ER 42 A Case Study of Radar Determined Rainfall as Compared to Rain Gage Measurements. Martin Ross. July 1971